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HIGH SPEED VACUUM PERFORMANCE OF GOLD PLATED MINIATURE BALL BEARINGS WITH VARIOUS RETAINER MATERIALS AND CONFIGURATIONS

by Harold E. Evans and Thomas W. Flatley

Goddard Space Flight Center
Greenbelt, Maryland

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SUMMARY

Metallic film lubrication of ball bearings is a possible answer to the evaporation, radiation resistance, and contamination problems associated with conventional lubricants in satellite applications. Success realized with gold plated miniature ball bearings in the development of a high speed satellite instrument prompted a detailed study of the performance of this type of bearing.

The first phase of the program which evolved was directed toward finding an acceptable retainer material and configuration. Bearings were tested in small 10,000 rpm motors in a special multi-port, oil-free vacuum system which is described in this report.

Two retainer types – fully machined retainers of "S"-Inconel and silver plated Circle "C" – proved outstanding and capable of providing about 1000 hours life in conjunction with gold plated balls and races. These retainers will be used in the next phase of the program which will involve various combinations of ball and raceway platings.

This report is an extension of the work reported in NASA Technical Note D-1339, "Bearings for Vacuum Operation Retainer Material and Design".

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HIGH SPEED VACUUM PERFORMANCE OF GOLD PLATED MINIATURE BALL BEARINGS WITH VARIOUS RETAINER MATERIALS AND CONFIGURATIONS

(Manuscript Received July 8, 1963)

by

Harold E. Evans and Thomas W. Fatley

Goddard Space Flight Center

INTRODUCTION

The environment of outer space presents four basic problems with regard to systems and components in which relative motion must be maintained for extended periods:

1. Extremely low ambient pressure (vacuum);
2. Radiation;
3. Meteoroids; and
4. Absence of gravitational effects.

Of these, the problem of low pressure is the most difficult to solve. Hermetic sealing of devices is not always possible or even desirable; hence some units must operate when exposed directly to the space environment. Examples of such devices are horizon seekers, star finders, radar antennas, solar paddles, and telescope pointing mechanisms.

Normal liquid and semi-solid grease lubricants have vapor pressures higher than the ambient pressures in outer space (estimated at 10^{-13} torr interplanetary and 10^{-16} torr interstellar)*; hence these lubricants evaporate rapidly. The absence of oxygen in space creates additional problems. Normally, oxide layers form on metallic surfaces and act as thin film lubricants; these layers are subject to rupturing, but reform quickly in the presence of oxygen. In space, however, this repair by re-oxidation cannot occur.

Radiation poses more of a problem in the materials and life sciences field than in friction and wear studies. Some lubricants undergo a phase change when irradiated, but this can probably be overcome more readily than the vacuum problem. For example, the approach taken in this investigation (thin metallic film lubrication) solves the radiation problem because metallic films are radiation-resistant.

*Bisson, E. E., "Friction and Bearing Problems in the Vacuum and Radiation Environments of Space," at course on Bearing Technology, University of California, Los Angeles, November, 1961, p. 2.

The presence of meteoroids becomes important where hermetically sealed systems are used: meteoroid impacts could destroy a hermetic seal.

The zero-g effect is not expected to be of major importance in the thin film study, but it could be a significant factor if a wet lubricant is to be contained in a system. In many applications the zero-g effect could be very beneficial, since it would greatly reduce the normal forces acting on the surfaces in contact.

Possible solutions to the friction and wear problems in a vacuum environment fall into five basic categories, involving the use of low vapor pressure oils and greases; laminar solids (MoS_2, PbO, etc.); metallic films; plastics; and ceramics (materials of extremely high elastic modulus). In this study, the metallic film approach is taken.

THIN FILM THEORY

It is well known that thin films such as oxide coatings have a marked effect on friction and wear between surfaces. It is also known that a certain degree of roughness exists even on a highly polished surface. Magnified many times, such a "polished" surface resembles a mountain range. When two surfaces move relative to each other, areas of extreme stress exist where these "mountains" come into contact. The stress levels reached at these interfaces are high enough to cause crushing of the "mountain tops."

Bowden and Tabor* and Merchant† advanced the adhesion theory of friction. This theory holds that crushing of the "mountain tops" creates small areas of plastic flow which result in small cold welds. Relative motion between parts then requires that shearing take place in the weld or in the base metal proper. The theory also states that a friction force is made up of a shear term and a ploughing term. The shear term represents the force required to break the welded junctions, and the ploughing term represents the force required to displace "mountain tops" of a softer material by a harder material. Experience has shown that the ploughing term is, in general, quite small and the shear term is the governing friction factor. Hence, friction is usually expressed only by the shear term:

$$\mu = \frac{S}{P},$$

where μ is the coefficient of friction, S the shear strength of welded junctions, and P the flow pressure.

Obviously μ can be reduced if the shear strength is decreased or the flow pressure is increased. It is unlikely that both of these properties will be found in one material. However, Bowden and Tabor

*Bowden, F. P., and Tabor, D., "The Friction and Lubrication of solids," Oxford: Clarendon Press, 1950.

†Merchant, M. E., "The Mechanism of Static Friction," *J. Appl. Phys.* 11(3):230, 1940.

demonstrated that the use of lead and indium, applied as low-shear-strength films on hard base materials, achieves both desirable effects. This soft film effect forms the basis for the program reported here.

BEARING PROGRAM

The investigation of thin soft metallic films as a means of lubricating ball bearings in a vacuum environment is being conducted in conjunction with New Hampshire Ball Bearings, Inc., of Peterborough, New Hampshire.

Some background information was available on gold-plated bearings, since these were used in the electric field meter flown on Explorer VIII (1960ξ). It was therefore decided that this bearing would be the initial "standard" test vehicle.

Investigation of Retainers

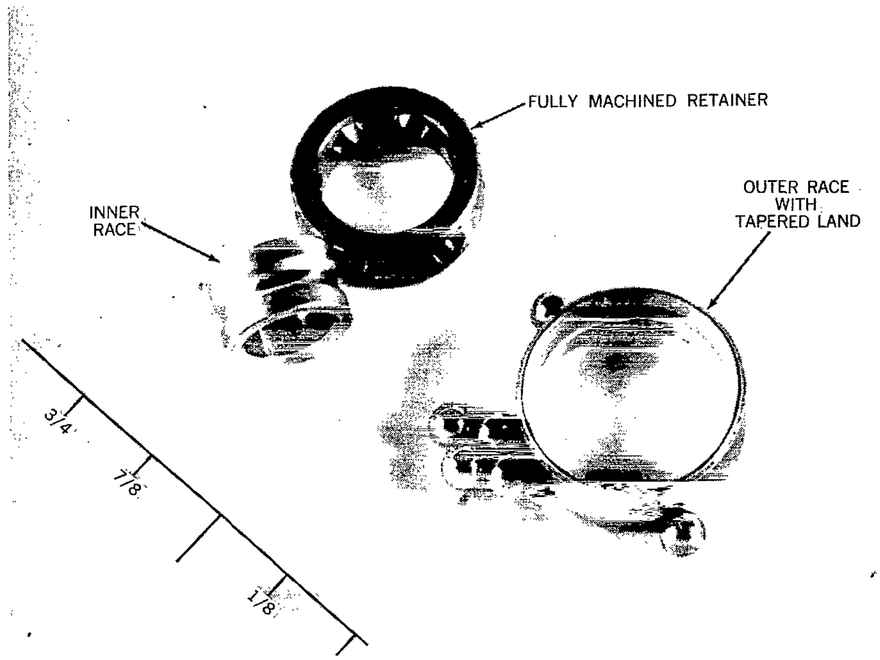
Since the major cause of bearing failure in the development of the electric field meter* was the retainer, the first phase of the study would consist of establishing the most promising retainer by using the "standard" gold-plated bearing. Phase II would then be conducted by using this new retainer and varying the types of plating. After the optimum retainer and plating materials were chosen, the final planned phase of the program would study plating procedures and thickness in an attempt to further improve performance.

All bearings tested had a 1/8 inch bore and gold-plated 440C stainless steel balls and races. R2-5 and R2-6 size bearings were run, the two types differing only in outer race thickness. Radial play was ordinarily in the 0.0005 to 0.0008 inch range. A typical set of bearing components is shown in Figure 1.

Most of the test involved bearings with fully machined retainers, but full complement (no retainer) and crown retainer configurations were also run. Retainer materials investigated included 2 percent beryllium copper, "Silnic" bronze (copper with zinc, nickel, and silicon), "S" Inconel (nickel with chromium, iron, and silicon), Circle "C" tool steel (18.5 percent tungsten), and 410 stainless steel. Four commercial plating sources (indicated by the designations D, R, LR and T) were employed. All were asked for "gold plate, 30 microinches thick". Table 1 shows the various retainer and plating combinations tested.

At the time a choice of Phase II retainer configuration was required, the "S" Inconel and silver plated Circle "C" materials appeared outstanding, so it was decided to proceed with both types. Table 2 outlines the basic Phase II program.

*Flatley, Thomas W., and Evans, Harold E., "The Development of the Electric Field Meter for the Explorer VIII Satellite (1960ξ)," NASA Technical Note D-1044, 1962.



Figure—1 Typical set of bearing components

Table 1

Bearing Configurations Tested and Phase I Test Results

Retainer Type	Retainer Plating	Ball Plating	Raceway Plating	Test No.	Running Time (hours)	Remarks
2% Beryllium Copper	None	D	D	1	329	
				2	12	
		R	R	3	71	
				4	4	
			D	5	68	
				6	5	
Silnic Bronze	None	D	D	7	159	
				8	80	
		R	R	9	156	
Gold Plated Silnic Bronze	D	D	D	10	369	
				11	279	
	R	R	R	12	39	
				13	32	
None (full complement)	—	D	D	14	9	Low voltage test
				15	9	Low voltage test
				16	87	Low voltage test
				17	775	No failure
		R	R	18	47	No failure
				19	47	No failure
Gold plated 410 stainless steel (crown)	D	D	D	20	477	
				21	142	
				22	311	

Table 1 (continued)

Bearing Configurations Tested and
Phase I Test Results

Retainer Type	Retainer Plating	Ball Plating	Raceway Plating	Test No.	Running Time (hours)	Remarks
S-Inconel	None	D	D	23	898	
				24	639	
		R	R	25	178	
				26	147	
				27	510	
		LR	LR	28	67	
				29	518	
Annealed Circle C	None	D	D	30	1	Low voltage test
				31	1	Low voltage test
Hardened and tempered Circle C	None	D	D	32	47	Low voltage test
				33	35	Low voltage test
				34	1	Low voltage test
				35	295	
Silver plated annealed Circle C	D	D	D	36	1049	No failure
				37	1661	
				38	183	Low voltage test
				39	35	Low voltage test
				40	598	No failure
				41	619	No failure
				42	785	No failure
		R	D	43	137	
				44	33	
				45	353	
				46	824	
		T-O	T-HG	47	460	
				48	16	
				49	70	
				50	16	
				51	544	
				52	1	
				53	12	
	R	R	R	54	332	
	LR	LR	LR	55	737	
				56	1455	
Silver plated hardened and tempered Circle C	D	D	D	57	731	No failure
				58	636	No failure
	LR	LR	LR	59	73	
				60	389	
Annealed Circle C (thin design)	None	D	D	61	9	
				62	45	
				63	441	
				64	21	
Hardened and tempered Circle C (thin design)	None	D	D	65	280	
				66	438	
				67	1111	

Vacuum System

Because the bearings were to operate without the benefit of oil film lubrication, a vacuum system completely free of oil diffusion pumps was required, since experience has shown that it is extremely difficult to isolate all pump oil from vacuum chambers even when extensive cold trapping and baffling are employed. To meet this requirement a special pumping system, employing ion-getter type high-vacuum pumping and a cryogenic roughing pump, was designed and built.

Since the test program called for a large number of bearing tests, a versatile system was required – one that would permit testing of many bearings at one time, and also allow access to each unit under test without disturbing the other tests. The system designed for use in the bearing test program is known as the Heptavac.

Table 2

Combinations of Retainer Materials, Ball Platings, and Raceway Platings Used in the Phase II Tests

Retainer Material	Ball Plating	Raceway Plating
Silver plated Circle "C"	Barium	Gold
		Silver
	Gold	Barium
		Silver
	Silver	Barium
		Gold
"S"-Inconel	Barium	Gold
		Silver
	Gold	Barium
		Silver
	Silver	Barium
		Gold

Figure 2 shows the layout of the system. Basically, it consists of a 1.44 liter main chamber surrounded by seven 0.16 liter individual test chambers and connected directly to a 40 liter/sec ion pump. Figure 3 shows a close-up view of a typical test chamber, which is connected to the main chamber by a 1-inch all-metal valve and has its own 8 liter/sec ion pump. In addition, a small 1/4-inch all-metal valve is included to vent the chamber to the atmosphere or to connect to the roughing pump as required. The chamber cap, like all other joints in the system, is sealed with a copper shear gasket. Electrical connections are made through a hermetically sealed connector which is silver-soldered in the cover cap.

The entire system is portable and, with pump magnets removed, may be baked to 550°C. The chief function of the main chamber is secondary roughing to accelerate the starting of the small pumps, but it is also available for use as a test chamber if required. The cryogenic roughing pump achieves pumping action through the sorption of gas by a molecular sieve chilled externally by liquid nitrogen.

Chamber pressures are determined with gages integral with the pump power supplies, operating on the principle that the pump current is a function of ambient pressure. Pressures in the high 10^{-9} torr region are obtainable in the empty chambers, but the presence of the motor coils, owing to their outgassing, limits test pressures to about 10^{-7} torr.

Test Setup

The basic element in the bearing test setup is a standard size-10 two-phase 400-cps induction motor. The torque-speed characteristics of this type of motor make it ideal for evaluating bearing

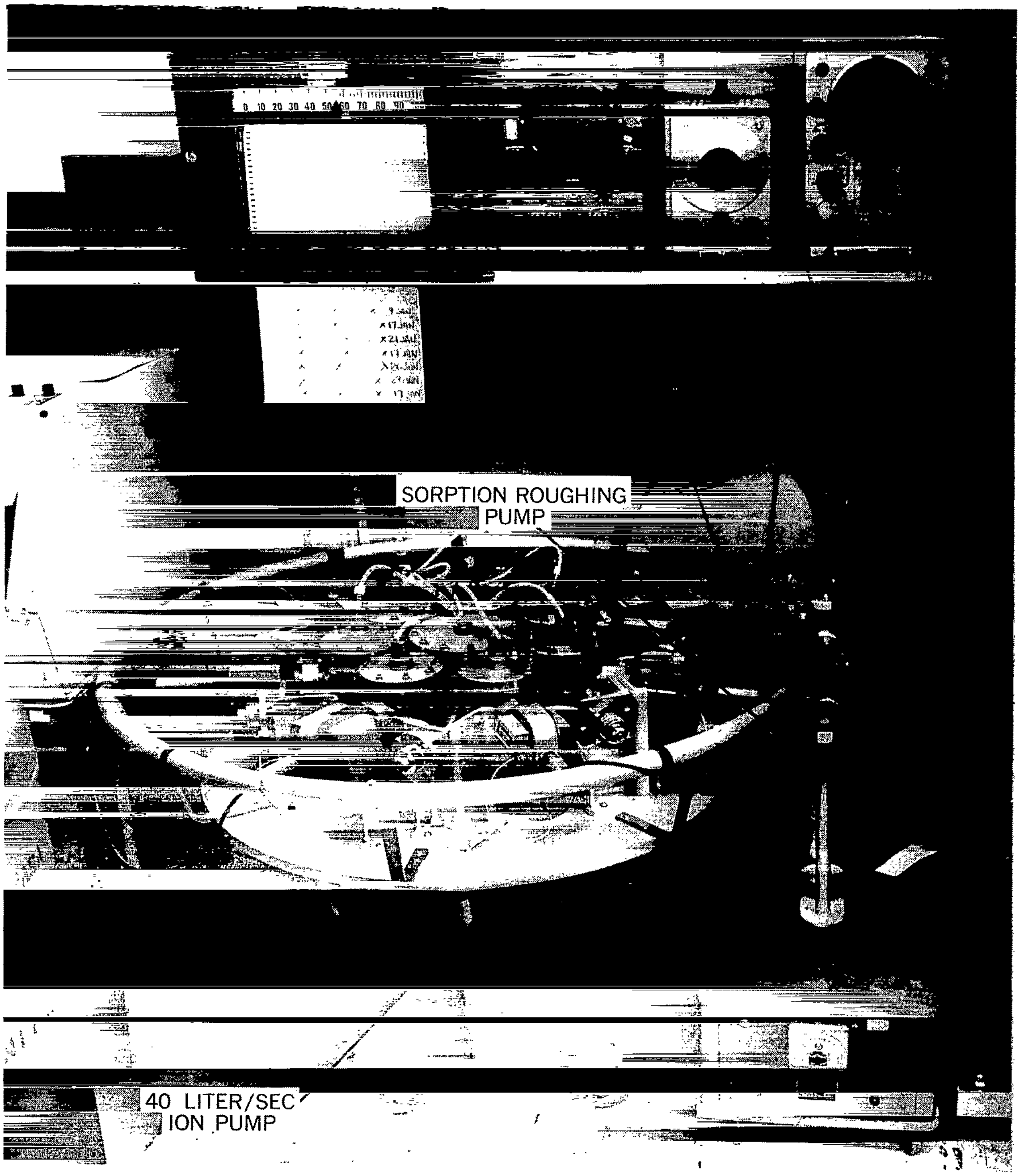


Figure 2—The Heptavac system.

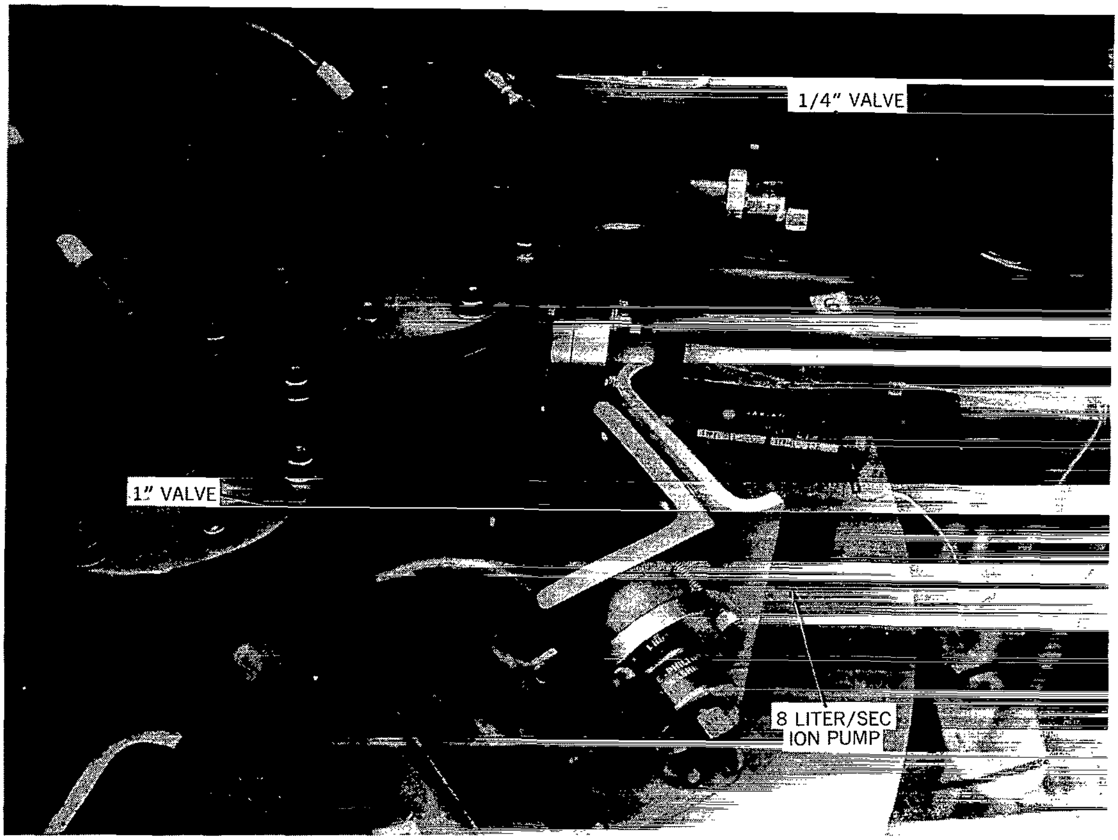


Figure 3—Typical Heptavac test chamber.

performance. The standard bearings in the motor are replaced by the bearings to be tested and a small iron 6-lobe wheel is attached to the motor shaft. Figure 4 shows the various components of the motor used as well as an assembled motor. Next to each bearing is a stainless-steel bushing which adapts the R2-5 size bearings to the motor housing.

The assembled motor is mounted in a fixture permanently attached to the test chamber cover cap (Figure 5). Thus mounted, the iron wheel completes a magnetic circuit which also includes a signal coil wrapped on a permanent magnet and magnetic stainless steel supports. When the wheel turns this circuit generates an alternating voltage whose frequency gives an accurate indication of the motor speed. The motor operates on 26 volts; its no-load speed is approximately 11,000 rpm and the speed varies linearly with the load. The stall torque is 0.26 oz-in.

The motor power and the generator signal pass through a hermetically sealed connector which is silver-soldered to the chamber cover cap. Also passing through this connector is the signal from a thermocouple connected to the motor housing; this signal is fed into a multichannel temperature recorder for temperature monitoring when required.

All units to be tested are assembled and disassembled in a dust-free cabinet to assure cleanliness.

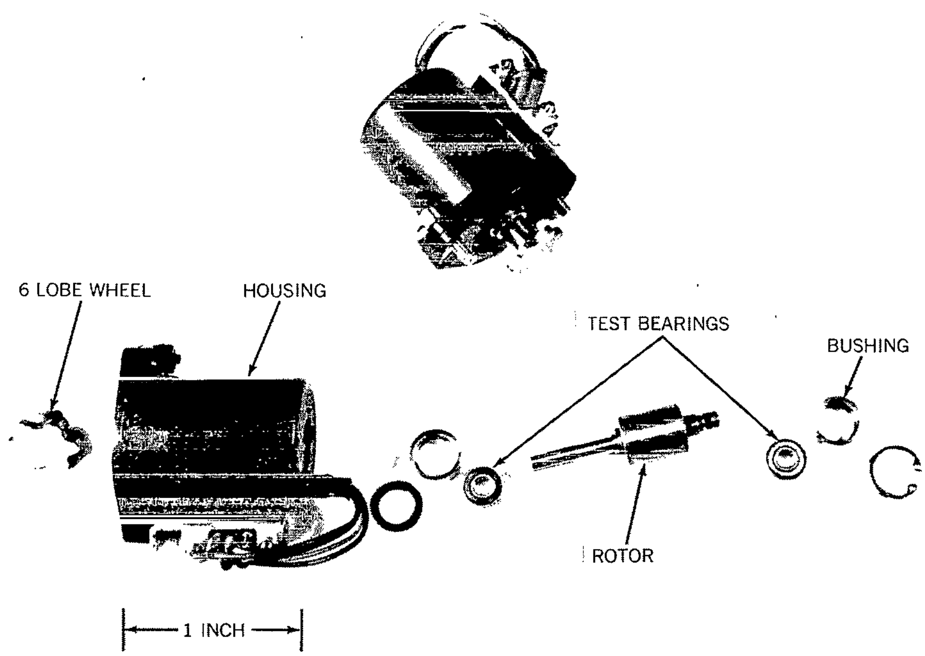


Figure 4—Assembled and disassembled motor for test setup.

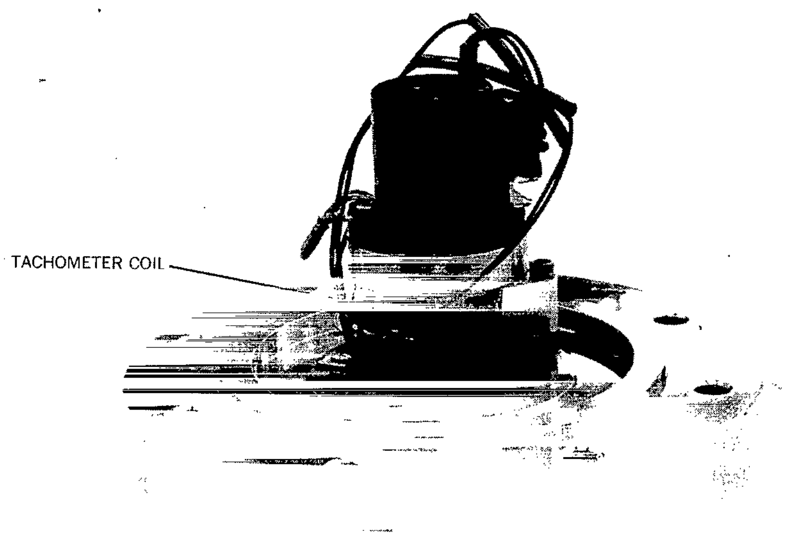


Figure 5—Motor assembly mounted on cover.

Instrumentation

The small signal generator in each bearing test unit was designed to produce an alternating voltage at a frequency six times greater than the motor speed as the motor shaft turns. Thus the number of cycles generated during a 10-second interval equals the speed of the motor in rpm. When the system is operating at full capacity, seven such signals are fed into a series of manual switches. These switches permit any one signal to be directed to any of seven inputs of an automatic sampling timer (Figure 6). A signal from the motor power supply is fed into the eighth input to the timer.

Operating on a 30-minute cycle, the timer samples each of the 8 input signals once per cycle for about 3-1/2 minutes. The signal being sampled is amplified and fed into an electronic counter with a 10-second gate time. The outputs from the counter and from a digital clock are fed into a digital recorder which prints out the test data in the form of a time and a motor speed once every 20 seconds. The record also includes a check on the power supply frequency, since that frequency will affect the motor speed. Figure 7 shows the basic instrumentation racks, which also include the ion pump power supplies for the vacuum system. To provide a check on motor speed fluctuations, the amplified input signal is sometimes fed into the X input of an oscilloscope. The output of an oscillator is fed into the Y input, and the speed consistency can be monitored by observing the Lissajous figures. This setup can also be used to determine the coast time when the motor power is cut off.

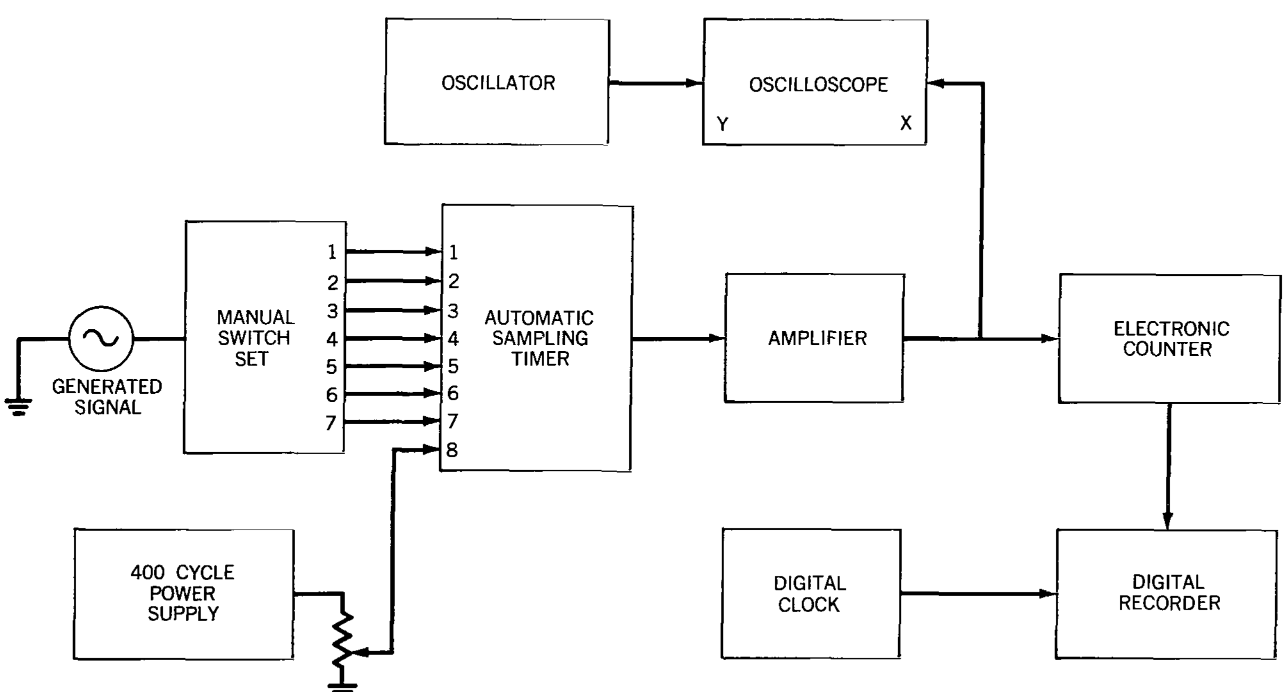


Figure 6—Instrumentation block diagram.

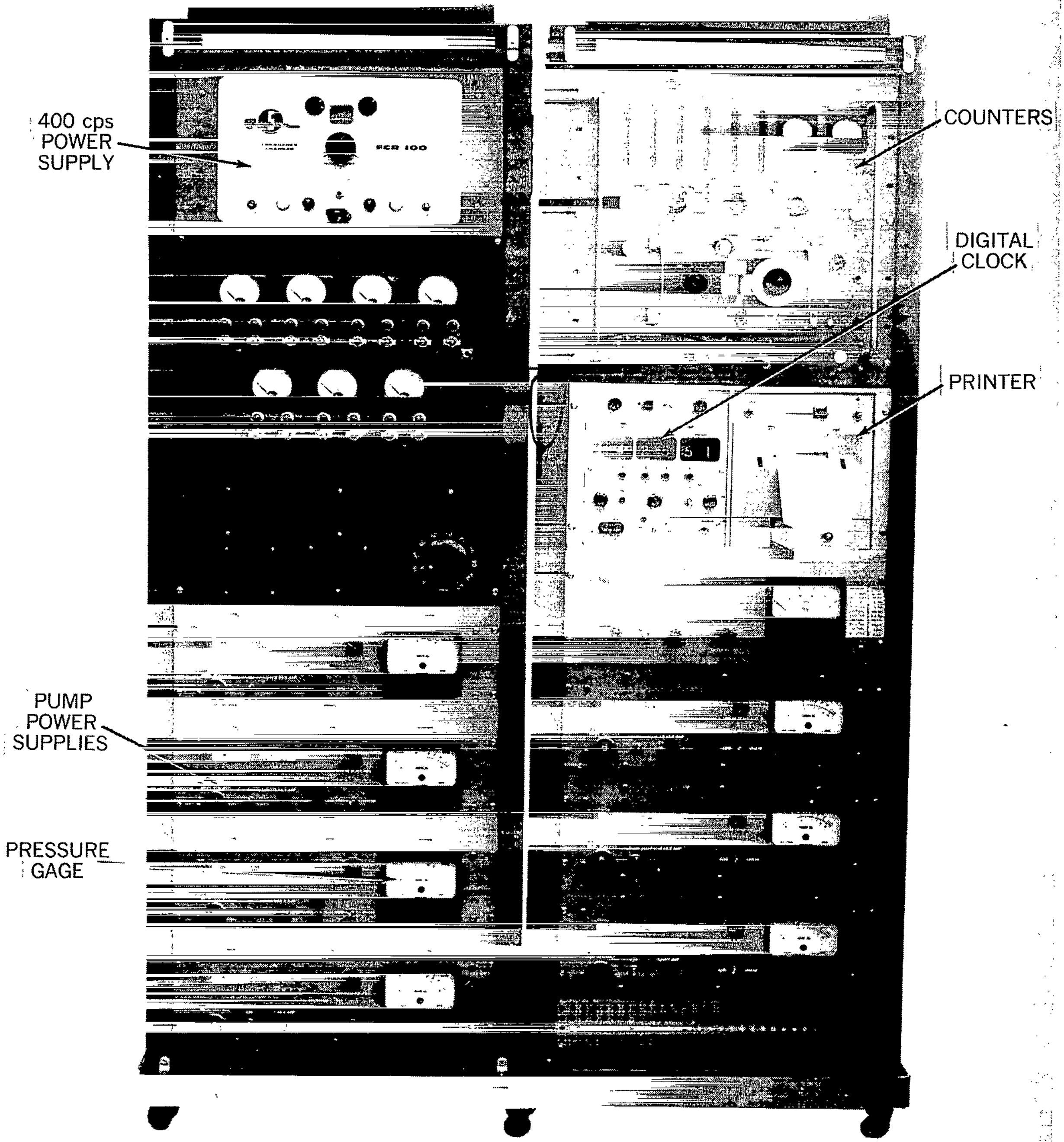


Figure 7—Bearing test instrumentation.

Autopsies

After being tested, all bearings were returned to the manufacturer where they were checked on a MIL-STD-206 torque tester, washed, torque-tested again, and checked for radial play. (These torque traces were then compared with the traces taken prior to testing.) The bearings were then disassembled, all their components were thoroughly inspected, and pertinent photomicrographs were taken. The contractor (New Hampshire Ball Bearings, Inc.) then provided a detailed report on each test which included all the numerical data accumulated and an analysis of the bearing performance.

RESULTS

The results of the Phase I testing are presented in Table 1. The tests are divided primarily according to retainer types, then subdivided with respect to the plating sources employed. In the "Remarks" column of the table "Low voltage test" indicates that the motor was operated with only 12 v ac applied. This reduced its stall torque to about 0.06 ounce-inch, and induced early "failures". Several tests were halted because of the priority of Phase II testing. They are identified by a "No failure" notation. The "thin design" referred to indicates retainers with reduced outside diameters to eliminate contact between the retainers and outer races.

During this program, bearing failures were caused by a loss of radial play due to a buildup of material on the balls and races and/or the accumulation of wear debris within the bearings. The performance of the various configurations tested provides a measure of their ability to maintain some internal clearance during operation.

Figures 8 through 12 show typical speed-time curves observed during the program. In general, an early loss of speed, indicating a period of relatively high torque operation, occurred. In the longer tests, this period was followed by a long fairly steady run and then catastrophic failure as one of the bearings seized. This "run-in" period was characterized by gold transfer between the balls and races, and in some cases the resulting bearing roughness was enough to cause premature failure. This was especially true with gold plates "R" and "T" where relatively large particle transfer and flaking took place. Plates "D" and "LR" seemed to transfer in finer particles, eventually wearing thin and burnishing, and thereby providing effective metallic film lubrication.

When the "run-in" period was survived, the retainer wear rate became an important factor. With the copper-base materials, this rate was excessive and the accumulation of retainer and gold plate debris led to early failures. The effect of gold plating the Silnic bronze is of interest. With plate "D", the retainer plating protected the ball pockets, delayed excessive wear, and nearly tripled the bearing life. With plate "R" however, plating the retainer shortened the life because of the previously mentioned mass transfer tendency of this plating.

The wear rate was less with the "S" Inconel, Circle "C", and 410 stainless, and in the case of the silver plated Circle "C" it was often negligible because a gold-silver alloy formed in the pockets and protected the base metal. With the harder materials retainer wear, when it began, generated small, abrasive particles. This debris often caused extensive damage to the ball and race platings and the

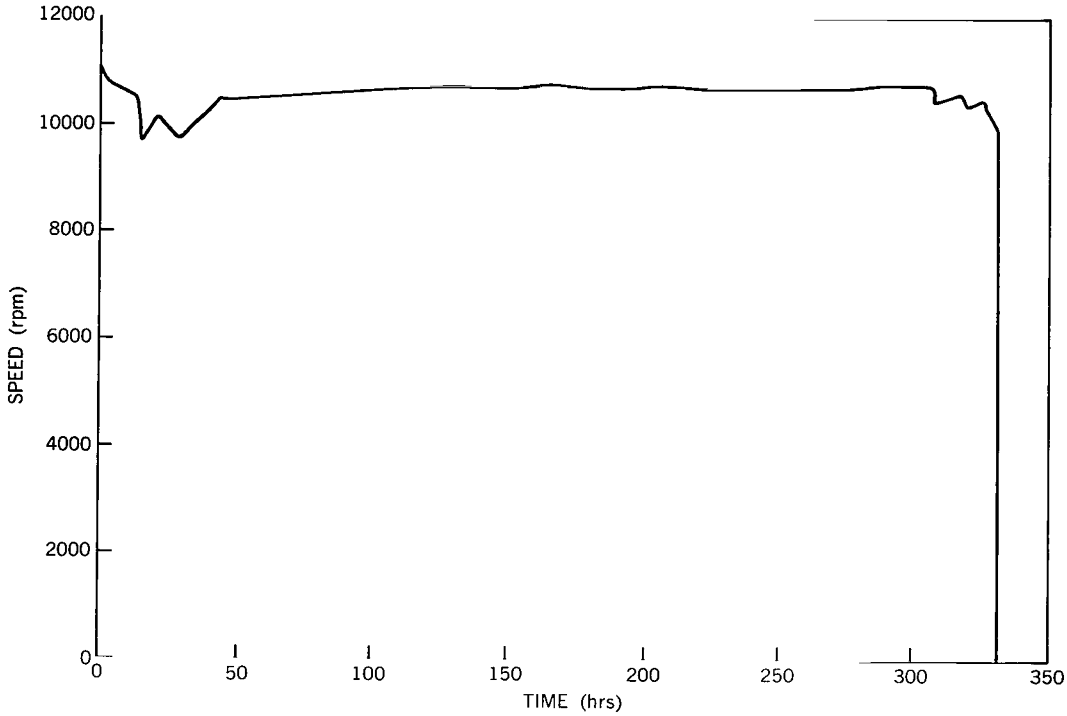


Figure 8—Speed-Time curve, Test 1.

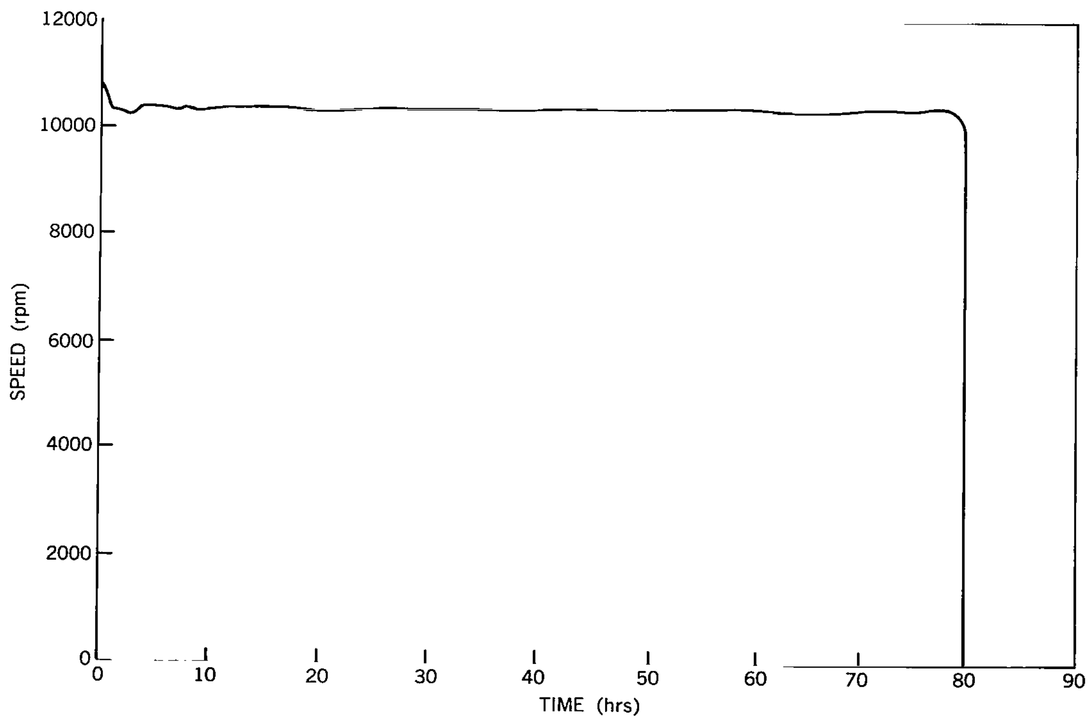


Figure 9—Speed-Time curve, Test 8.

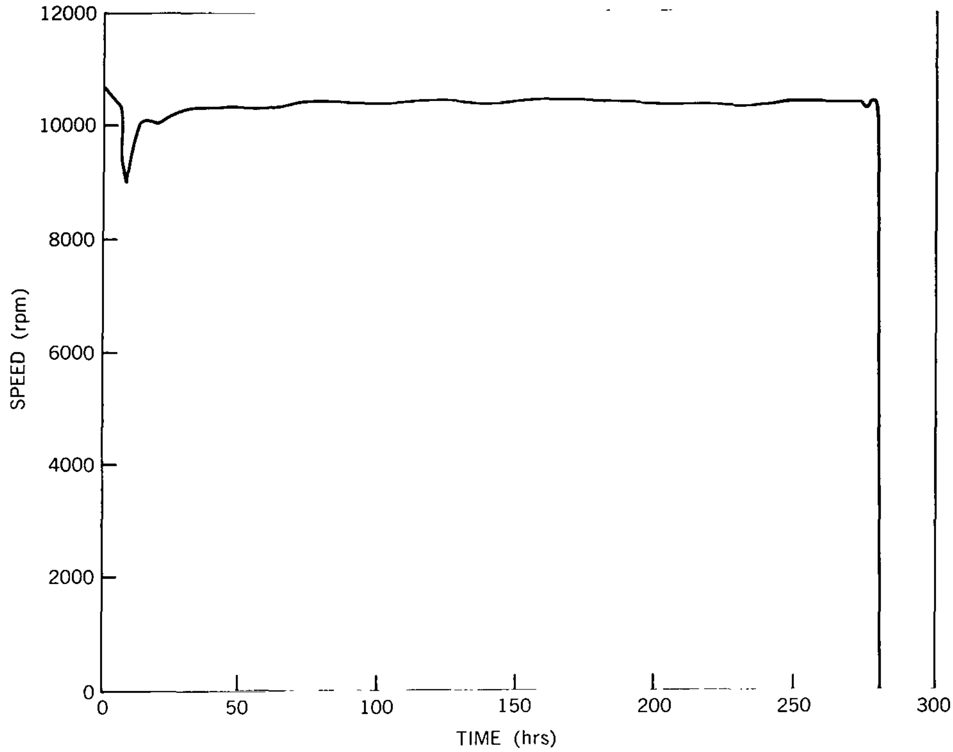


Figure 10–Speed-Time curve, Test 11.

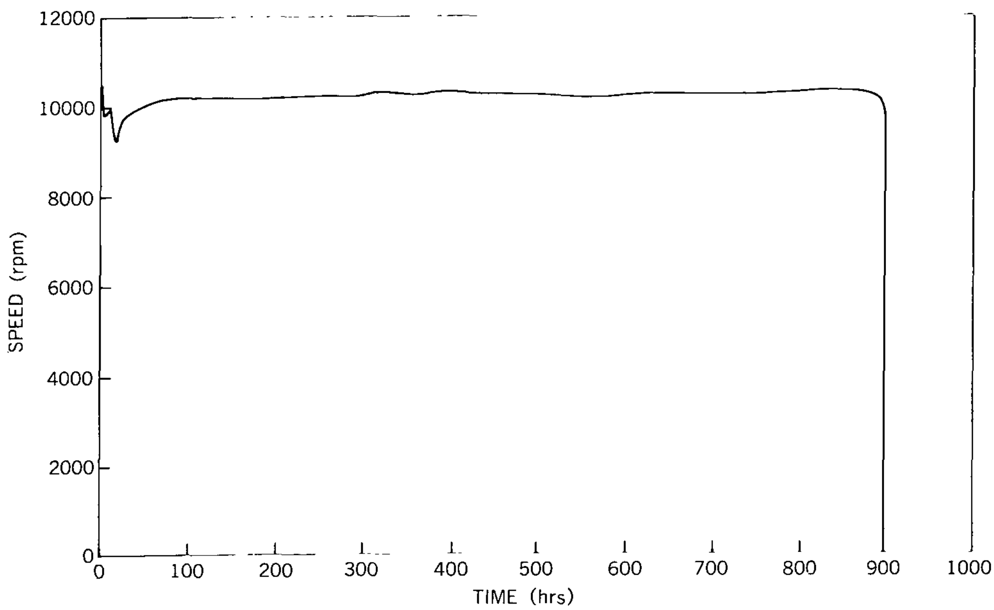


Figure 11–Speed-Time curve, Test 23.

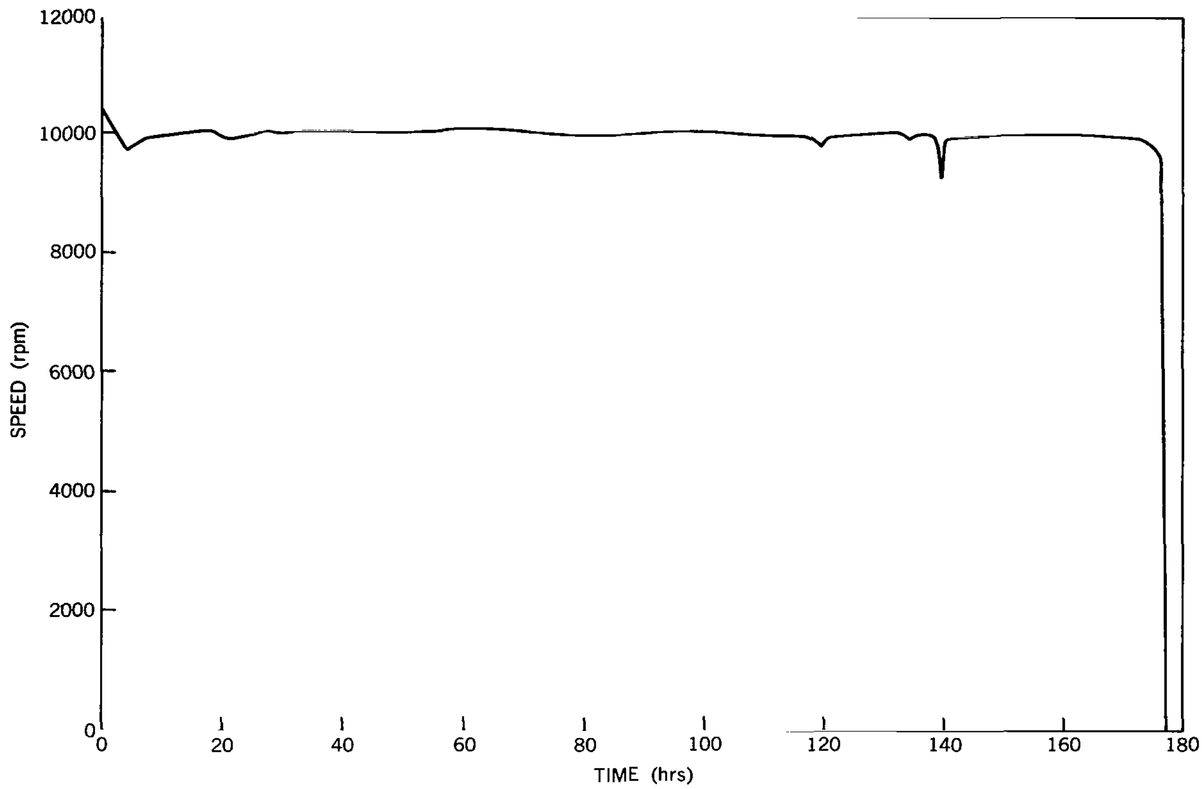


Figure 12—Speed-Time curve, Test 25.

base metal itself, but in general it was loose and powdery and did not tend to build up on the contact surfaces. The bearings therefore continued to run.

Seventeen pairs of bearings ran for over 500 hours. Many of the important results of this phase of the program are demonstrated by the bar graph shown in Figure 13. Notice the following significant features:

1. None of these tests involved a copper-base retainer material, or the crown retainer configuration.
2. The only-full complement bearing test in which full power was applied and which was allowed to run for a significant length of time is included.
3. Tests involving silver plated Circle "C" and "S" Inconel retainers and plating "D" and "LR" predominate.

On the other hand, results not apparent from the bar graph include:

1. In cases where bearings differed only in plating source, plates "D" and "LR" consistently outperformed plates "R" and "T".
2. The thin retainer design proved inadequate and performed erratically.

TEST NO.	RETAINER TYPE	RETAINER PLATING	BALL PLATING	RACEWAY PLATING
17	None (full complement)		D	D
23	S-Inconel	None	D	D
24	S-Inconel	None	D	D
27	S-Inconel	None	LR	LR
29	S-Inconel	None	LR	LR
36	Silver plated annealed Circle C	D	D	D
37	Silver plated annealed Circle C	D	D	D
40	Silver plated annealed Circle C	D	D	D
41	Silver plated annealed Circle C	D	D	D
42	Silver plated annealed Circle C	D	D	D
46	Silver plated annealed Circle C	D	T-O	T-HG
51	Silver plated annealed Circle C	D	T-O	T-HG
55	Silver plated annealed Circle C	LR	LR	LR
56	Silver plated annealed Circle C	LR	LR	LR
57	Silver plated hardened and tempered Circle C	D	D	D
58	Silver plated hardened and tempered Circle C	D	D	D
67	Hardened and tempered Circle C (thin design)	None	D	D

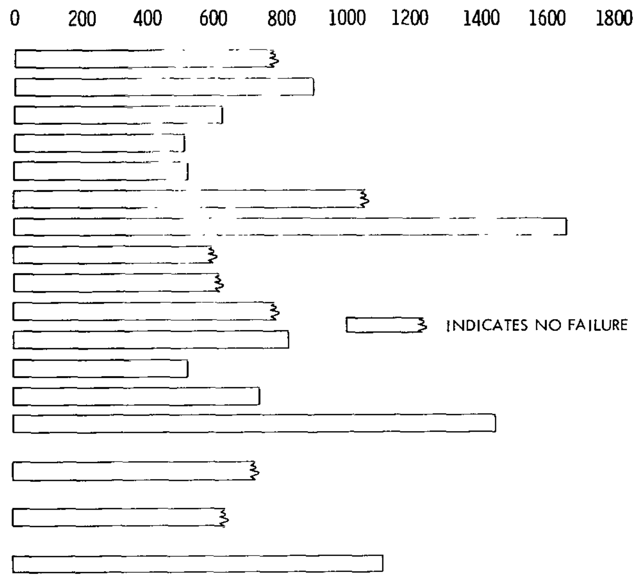


Figure 13—Phase I 500-hour runs.

3. The effects of hardening the Circle "C" material were not adequately determined because most of the tests set up for this purpose either were low voltage tests or involved the thin retainer design.

Metallurgical evaluation of the plating produced by the various sources was not a part of this program. This means that these sources can be judged only on the basis of bearing performance, so plates "D" and "LR" will again be used in the second phase of the program.

Occasional premature failures experienced with the better bearing types (e.g., Tests 28 and 59) point out a basic reliability problem with metallic film lubricated bearings. The fact that a single loosened particle can cause instantaneous failure means that extreme care must be taken in the quality control and inspection phases of bearing production A small local area of poor plate adhesion can lead to rapid seizure. The extent of plating control required will be one of the subjects for study in Phase III of the program. Load and speed variables will also be introduced in that phase.

CONCLUDING REMARKS

To date, this study has been a research program of very narrow scope but some general comments can be made on the basis of the experience gained.

Running motors in the vacuum was expedient in many ways, but it does introduce the possibility of outgassing contamination. Since the bearing surfaces were the hottest areas within the chamber, and since no evidence of contamination was observed elsewhere it seems likely that the motor outgassing was not a significant factor but it remains an unknown quantity. This testing procedure will continue in the next phase of the program, but Phase III testing will be carried out in a new system with a magnetic coupling drive.

Metallic film lubrication of ball bearings for vacuum operation seems promising. The complete elimination of environment contamination by lubricants and the electrical conductivity and radiation resistance of this type of bearing make it potentially useful for space work if the performance and reliability can be improved. The inherent operating noise and vibration and the radial play requirements could limit its use, however.